

Laser-induced spark for measurements of the fuel-to-air ratio of a combustible mixture[☆]

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Abstract

This work investigates the use of the laser-induced gas breakdown for fuel-to-air ratio measurements. In essence, we examine the late time behavior of the line radiation at the wavelength of the H_{α} -lines and the O I triplet emitted from the laser-induced spark in CH_4 -air mixtures. Sparks were produced using a single-mode, Q-switched Nd-YAG laser. The laser produced a beam of 6 mm in diameter at the wavelength of 1064 nm and a pulse duration of 5.5 ns. For the equivalence ratio from 0.1 to 5.0, the radiation intensity ratio of the H_{α} -lines to the O I triplet increased linearly with the equivalence ratio. For the laser energy from 10 to 50 mJ it was independent of the laser energy when the laser energy was higher than 20 mJ. The technique, therefore, has a potential for measuring the fuel-to-air ratio of a combustible flow environment. Published by Elsevier Science Ltd.

Keywords: Laser-induced spark; Fuel-to-air ratio; CH_4 -air mixtures

1. Introduction

In many combustion systems fuel and air are injected into the combustor where they mix, ignite and burn. In these systems the role of the mixing process cannot be understated. Bad mixing produces more unwanted species, higher levels of combustion instability and localized flame extinction than good mixing. The term 'bad' refers to the situation that the distribution of the fuel-to-air ratio is not uniform in both space and time. Good mixing has a single-valued output fuel-to-air distribution. Therefore, real-time measurement of the distribution of the fuel-to-air ratio inside these combustion systems is very important. Optical techniques such as the laser-induced fluorescence, the laser Raman spectroscopy, etc. have been developed successfully for combustion species and temperature measurements, however, techniques for measuring the fuel-to-air ratio have not been available. The laser-induced breakdown spectroscopy (LIBS) is a useful optical diagnostic technique for determining the elemental compositions of liquids, solids, and gases [1–7]. In the LIBS technique, when a sufficiently high energy laser pulse is focused into a small volume, a spark plasma is created. The plasma then emits a wide spectrum of light. There are two main contributions to the

emitted spectrum: the spectrally broad band background continuum due to the luminous plasma, and the line radiation due to the ionized gas species. The continuum contribution is significant during the early stage of the spark development, while the contribution of the line radiation is dominant during the plasma cooling stage. Since excited species in the plasma emit light with a variation of the intensity and wavelength, these spectral lines are used to determine the types and quantities of species present.

Phuoc and White [8] reported that line radiation from the laser-spark created in CH_4 has a distinct and strong H_{α} -line centered at 656.3 nm which is emitted by electronically excited hydrogen dissociated from the methane fuel. For sparks created in air the strongest line radiation is at the wavelength of the O I triplet near 777 nm. Thus, by examining the relative intensities of these spectral lines from the laser spark created in CH_4 -air mixture one should be able to determine its fuel-to-air ratio.

2. Experimental

The experimental apparatus used in this study was described by Phuoc and White [8]. Sparks were produced using a single-mode, Q-switched Nd-YAG laser. The laser produces a 0.6-cm-diameter beam at a wavelength of 1064 nm with 5.5 ns pulse duration. The beam was focused by a 100 mm focal length lens after passing through a

1–99% variable beam splitter. With this laser system, the focal spot diameter and length are estimated to be 22.5 and 345 μm , respectively. Methane, (99.99% purity), and air, (21% oxygen), from high-pressure cylinders were delivered to the ignition cell using a gas handling system with precise gas flow controllers.

For space-resolved studies, line emissions were monitored using a Multichannel Instaspec IV CCD detection system. It consisted of a front-illuminated 1024×128 pixel format CCD detector head, and an imaging spectrograph. The spectrograph was equipped with three gratings covering a spectrum of 250–900 nm. The emission light from the spark plasma was collected using a single-track fiber optic cable and a lens speed ($F/\#$) matcher attached to the entrance slit of the spectrograph. The lens speed matcher was used to match the fiber cable, which has an $F/\#$ of about 2, to the input of the spectrograph which has an $F/\#$ of about 4. The detector was operated under full-vertical binning mode.

3. Results and discussion

Fig. 1 shows a typical space-resolved spectrum of 160 nm wide that was measured from the laser-induced spark in CH_4 –air mixture. The laser pulse energy was 24 mJ. Line emissions at the wavelengths of the O I triplet near 777 nm and the H_α -lines centered at 656.3 nm were distinct and strong. Some rather weak emission lines at the wavelengths of N I and O I in the region from 740 to 749 nm and near 795 nm were also observed. Use of the line intensities for accurately measuring the fuel-to-air ratio of a combustible mixture requires that they must respond linearly with the fuel and air fractions and the intensity ratios must be insensitive to the laser energy. To check if these requirements are satisfied we conducted two separate tests. In the first experiment we kept the laser energy constant at about 24 mJ and

varied the equivalence ratio from 0.1 to 5. In the second test, we varied the laser energy from about 10 to 50 mJ and kept the equivalence ratio constant at 0.5 and 2.4. The results are shown in Figs. 2 and 3. Several observations can be made from these figures: (i) although the fluctuation in the measured intensity around its averaged value was significant, the fluctuation in the intensity ratio was very much less significant. The fluctuation in the intensity is due to the probabilistic behavior of the laser-induced gas breakdown process. It depends on many factors including the fuel/air fraction, the laser energy, and the laser firing mode. For this work, it was observed that the fluctuation was significant and could be up to 20% of the average value when single firing mode was used but it became less significant when the laser was firing continuously. (ii) The intensities of the H_α -lines and the O I triplet responded linearly when the equivalence ratio increased, and they increased linearly as the laser energies increased. The ratio of the intensity, however, increased when the laser energy was below about 20 mJ and it became independent of the laser energy when it was higher than 20 mJ. Thus, within the limits of the intensity fluctuation, the requirements mentioned above are satisfied.

4. Measuring the fuel-to-air equivalence ratio of a jet diffusion flame

In order to demonstrate the potential of the laser-induced gas breakdown for in situ measuring the distribution of the fuel and air concentrations we have conducted a study on the laser ignition of a jet diffusion flame [9]. In the study, the gas jet was produced using a contoured stainless steel nozzle with an inlet diameter of 2.5 cm and a flat exit tip diameter of 0.15 cm. It is known that when a fuel jet enters quiescent air, jet expansion and air entrainment occur. Entrained air mixes with the fuel to form a flammable mixture in the flow

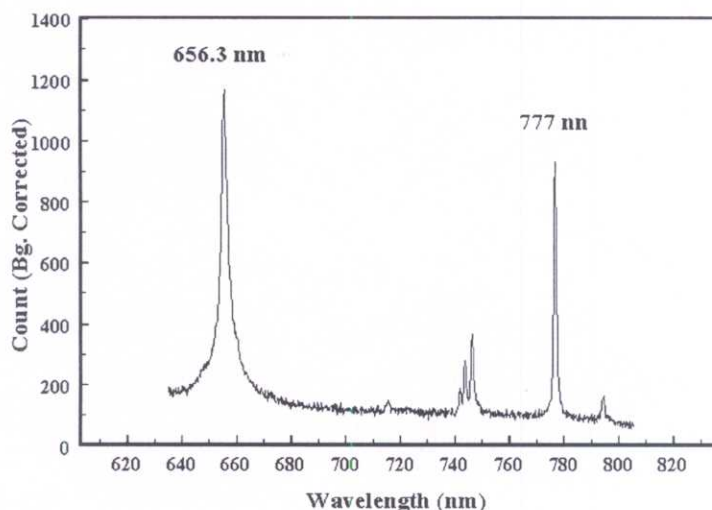


Fig. 1. A typical space-resolved spectrum of the laser-spark created in the stoichiometric CH_4 –air mixture. The laser pulse energy was 24 mJ.

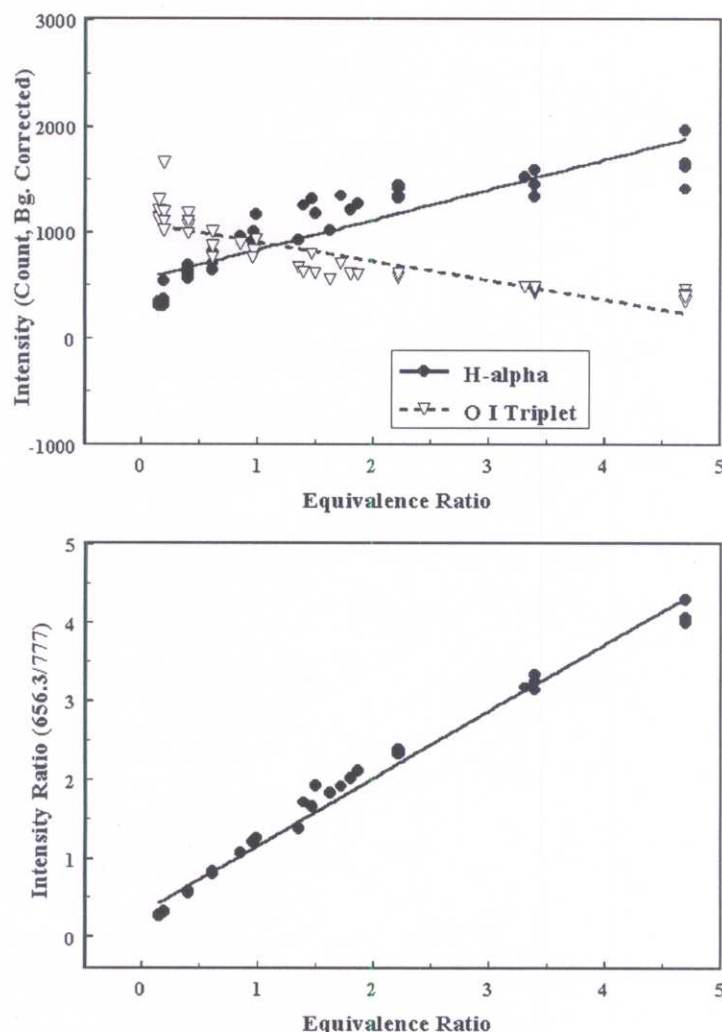


Fig. 2. Linear response of the radiation intensity of the H_{α} -lines (656.3 nm) and the O I triplet (near 777 nm) and the intensity ratio of the H_{α} -lines to the O I triplet with respect to the increase in the equivalence ratio; (CH_4 -air mixture; laser pulse energy = 24 mJ).

field. Since the mixing rate in this case depends on the turbulent interaction between the jet and the entrained air (which depends strongly on the jet velocity), the fuel and air concentrations across the jet and along its axis are different. Such a mixing pattern is typically shown in Fig. 4 for two locations. At 48.5 mm above the nozzle tip, the flammable region was created having its equivalence ratio decreasing from rich (about 1.6) on the jet axis to the stoichiometric value in the region 5–6 mm off the jet axis and to lean on moving radially further toward the air side. At 86 mm above the nozzle tip, since the air had enough time to penetrate deeper into the jet, the equivalence ratio remained near 1 from the jet axis out to 3 mm off the jet axis (two times the jet diameter). It then decreased rapidly to the lean side towards the air side.

In Fig. 5 we present the distributions of the equivalence ratio together with the ignition probability across the jet. The jet flow rate was $70 \text{ cm}^3/\text{s}$ ($Re = 2173$) at the location

was at 48.5 mm above the nozzle tip. The ignition probability was defined as the ratio of the number of the successful ignition events divided by the total number of breakdown sparks. Since the success or failure of an ignition event depends strongly on many factors such as turbulence intensity, velocity gradient, and the equivalence ratio at the location where the ignition source is applied, the distributions of the ignition probability and the equivalence ratio of a jet diffusion flame should have the same pattern. Thus, the results shown in Fig. 5 support the validity of the equivalence ratio reported earlier.

5. Conclusions

We have investigated the use of the laser-induced gas breakdown for measuring the fuel-to-air ratio of CH_4 -air mixtures. By examining the response of the radiation

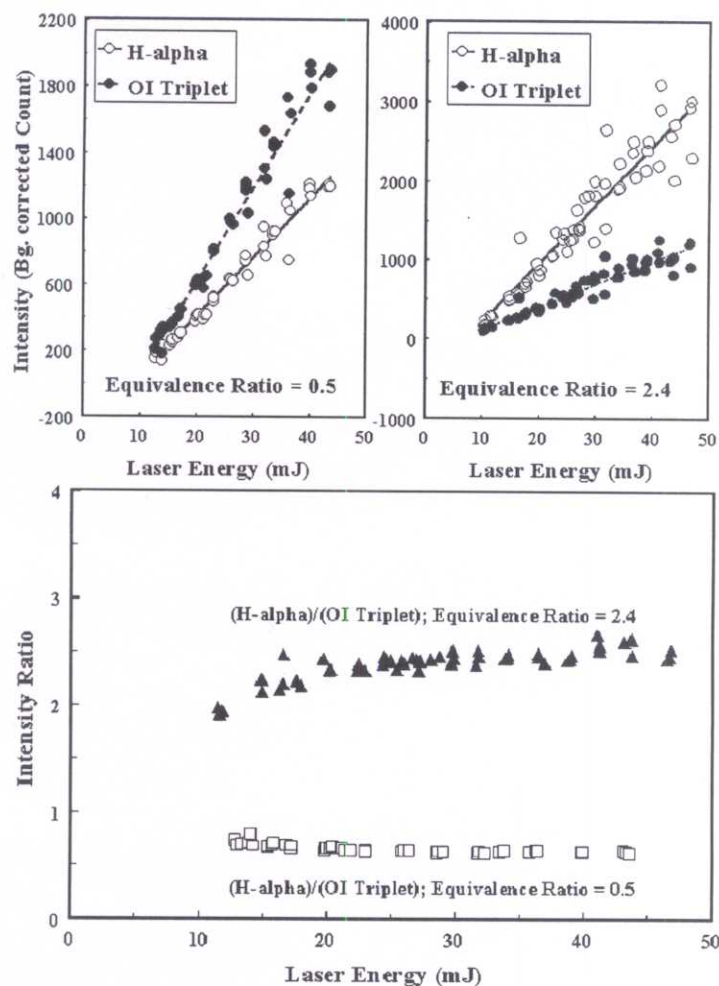


Fig. 3. Effects of the laser energy on the radiation intensity of the H α -lines (656.3 nm) and the O I triplet (near 777 nm) and the intensity ratio of the H α -lines to the O I triplet; (CH $_4$ -air mixture with equivalence ratio of 0.5 and 2.4 laser pulse energy from 10 to 50 mJ).

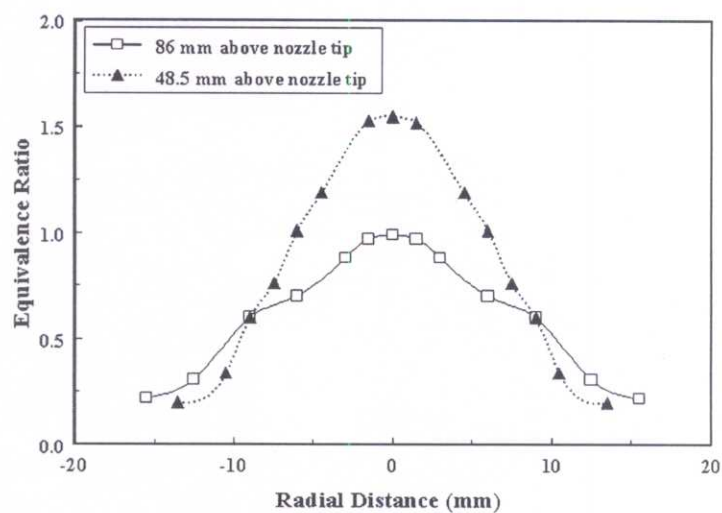


Fig. 4. Typical equivalence ratio across the methane jet diffusion flame (70 cm 3 /s; Re = 2173).

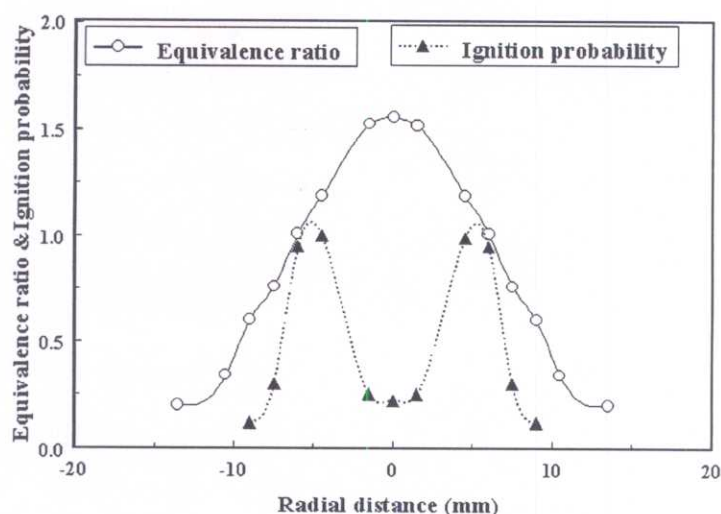


Fig. 5. Ignition probability and equivalence ratio in the radial locations; (jet flow rate: $70 \text{ cm}^3/\text{s}$; $Re = 2173$) at 48.5 mm above the nozzle tip).

intensity ratio of the H_α -lines and the O I triplet as a function of the equivalence ratio and the laser energy we found that the LIBS has a potential for in situ and nonintrusive measurements of the fuel-to-air ratio of a combustible environment.

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